3D COMPUTATIONAL TESTING OF MICROSTRUCTURES OF PARTICLE REINFORCED METAL MATRIX COMPOSITES

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ABSTRACT

3D FE (finite element) simulations of the deformation and damage evolution of SiC particle reinforced Al composites are carried out for different microstructures of the composites. A program for the automatic generation and the design of FE meshes for different 3D microstructures of composites is developed. Numerical testing of composites with random, regular, clustered and gradient arrangements of spherical particles is carried out. The fraction of failed particles and the tensile stress-strain curves were determined numerically for each of the microstructures. It was found that failure strain of a composite increases in the following order: clustered < regular < random < gradient microstructure.

INTRODUCTION

Due to their lightness, high strength and high stiffness, metal matrix composites with ceramic reinforcements are widely used industrially. An improvement of the strength of the materials can be of great benefit for the aviation and automobile industries. This can be achieved, among other ways, by optimizing the microstructure of the materials. One of the ways to determine the optimal microstructures is to use numerical (micro- and mesomechanical) simulations of deformation and failure processes in the materials, and to carry out the "virtual testing" of different microstructures of materials [1].

The purpose of this work was to analyze the effect of microstructures of particle-reinforced metal matrix composites on the deformation and damage resistance of the composites by carrying out 3D numerical simulations of deformation and damage evolution in the composite. In order to generate and mesh 3D artificial microstructures of the composites, a new program for the automatic design of three-dimensional FE meshes for particle-reinforced materials with different particle arrangements, shapes and types of localization (clustered, gradient), was developed. Using the program, we simulated numerically the mechanical behavior and damage evolution in the materials with different (artificially designed) microstructures, and determined the amount of failed particles and the tensile stress-strain curves for each of the microstructures. On the basis of the numerical experiments, the effect of the particle arrangement on the strength and damage resistance of the composite has been clarified.

GENERATION OF 3D ARTIFICIAL MICROSTRUCTURES AND AUTHOMATIC DESIGN OF FE MESHES

In order to generate and mesh 3D artificial microstructures of the composites, a new program “Meso3D“ [10] for the automatic design of three-dimensional FE meshes for particle-reinforced materials with different particle arrangements, shapes and types of localization (clustered, gradient), was developed. The program works with the commercial software MSC/PATRAN and produces artificial microstructures (i.e., different arrangements of round and ellipsoidal inclusions in a matrix) on the basis of given parameters and probability distributions of particle coordinates and sizes, and generates the finite element databases for the computational testing of the materials with the required artificial microstructures. The designed microstructures are meshed with tetrahedral elements using the free meshing technique.

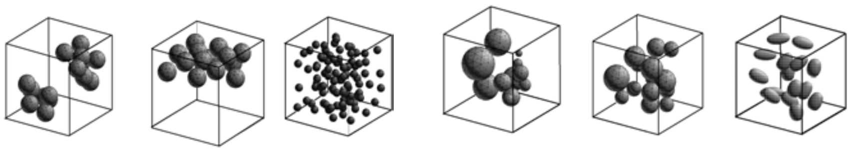

Figure 1. Examples of designed artificial microstructures.

The microstructures with the random particles arrangement are generated using the uniform random number generator. The coordinates of the centers of particles for the regular (and any other pre-defined) particles arrangements can be read from a text input file. In order to generate the localized particle arrangements, like clustered, layered and gradient particle arrangements, the coordinates of the particle centers are calculated as random values distributed by the Gauss law. The mean values of the corresponding normal distribution of the coordinates of particle centers are assumed to be the coordinates of a center of a cluster (for the clustered structure), or the Y- or Z-coordinate of the border of the box (for the gradient microstructure). The standard deviations of the distribution can be varied, from highly clustered or highly gradient arrangements (very small deviation) to the fast uniformly random particle arrangements (a deviation comparable with the box size). Figure 1 shows some examples of the artificial microstructures designed with the use of the program “Meso3D”.

NUMERICAL MODEL AND PROPERTIES OF PHASES

Using the program “Meso3D” [10], we simulated the mechanical behavior and damage evolution in the materials with different (artificially designed) microstructures, and determined the amount of failed particles and the tensile stress-strain curves for each of the microstructures.

The problem was solved in the framework of the embedded cell approach [1, 7]. The FE meshes of the composites with different microstructures (a given amount of SiC particles in a box 10 x 10 x 10 mm, filled with elastoplastic Al matrix), generated with the use of the program “Meso3D” and commercial code MSC/PATRAN, were placed in a bigger box 14 x 14 x 14 mm. The embedding zone behaved as a composite with averaged properties, i.e. as an elastic-plastic material. The SiC particles behaved as elastic isotropic damageable solids, characterized by Young modulus E_P=485 GPa, Poisson’s ratio 0.165 and the local damage criterion, discussed below. The Al matrix was modeled as isotropic elasto-plastic solid, with Young modulus E_M=73 GPa, and Poisson’s ratio

0.345. The experimental stress-strain curve for the Al matrix was taken from [14]. The elements in the embedding were assigned the averaged mechanical properties of the Al/SiC composite, with Young modulus E_{Av}=75.7 GPa (for the volume content 10%) and E_{Av}=88.4 GPa (for 15%), and Poisson's ratio 0.323 taken from [11]. The elasto-plastic stress –strain curve for the composite (embedding) was taken from [11] as well. When approximating the experimental stress-strain curve by the deformation theory flow relation $\sigma_y=\sigma_{yn}+h\varepsilon_{pl}^n$, where σ_y -the actual flow stress, σ_{yn} - the initial yield stress, and εpl- the accumulated equivalent plastic strain, h and n - hardening coefficient and the hardening exponent, the parameters of the curve are as follows: σ_{yn} =205 MPa, h= 457 MPa, n=0.20. For the composite (embedding), the parameters were: σ_{yn} =216 MPa, h= 525.4 MPa, n=0.25. We considered cells with 5, 10 and 15 particles, the volume content of the inclusion phase was 2.5%, 5%, 10% and 15%. Totally, the models contained about 30000 elements. The radii of particles were calculated from the prescribed volume content and particle amount in the box, and were as follows: 1.1676 mm (volume content/VC=10%, N=15), 0.9267 mm (VC=5%, N=15), 1.3365 mm (VC=10%, N=10) and 1.0608 (VC=5%, N=10). The nodes at the upper surface of the box were connected, and the displacement was applied to only one node. The model was subject to the uniaxial tensile displacement loading, 2.0 mm. The uniaxial tensile response of each microstructure was computed by the finite element method. The simulations were done with ABAQUS/Standard.

Only damage in SiC particles was considered at this stage of the work. The damage was modeled using the element weakening technique [6]. The finite elements in which the damage criterion (maximum principal stress) exceeded a critical value, were considered to be failed, and the Young modulus of these elements was set to a very low value (50 Pa). An ABAQUS Subroutine USRFLD, which allows to simulate the local damage growth as a weakening of finite elements was developed. According to [13], the SiC particles in AlSiC composites fail, if the critical maximum principal stress in SiC particle exceeds 1500 MPa. This value was used in our simulations as a criterion of the failure of SiC particles as well.

EFFECT OF MICROSTRUCTURE OF THE AL/SIC COMPOSITE ON THE DAMAGE RESISTANCE

The effects of particles arrangement and localization on the deformation and damage evolution in the composite were considered. Two types of the gradient particle arrangements were considered: an arrangement of particle with the vector of gradient (from low particle concentration region to a high particle concentration region) coinciding with the loading direction (called in the following a "gradient Y" microstructure), and a microstructure with the gradient vector perpendicular to the loading vector (called in the following "gradient Z" microstructure). The standard deviations of the normal distribution of the Y or Z coordinates of the particle centers (for the Y and Z gradient microstructures, respectively) were taken 2 mm, what ensured rather high degree of gradient. The same standard deviations were taken for the clustered particle arrangements. Figure 2 shows the tensile stress-strain curves and the amount of failed particles in the box plotted versus the far-field applied strain for the random, regular, clustered and gradient microstructures (for 15 particles, VC =10%).
Figure 3 gives the distributions of equivalent plastic strains on the boundaries of the microstructure box, and on the particle/matrix interfaces in the microstructures with random particle arrangements (15 particles, VC =10%). It can be seen from Figure 3 that the particle arrangement hardly influences the effective response of the material in elastic area or at small plastic deformation. The influence of the type of particle arrangement on the effective response of

the material becomes significant only at the load at which the particles begin to fail. However, after the particle failure begins, the effect of particle arrangement increases with increasing the applied load.

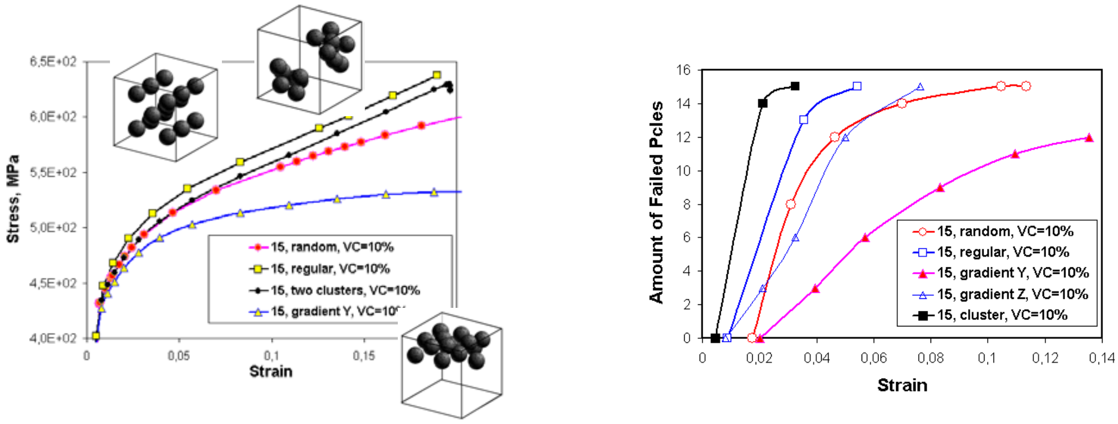

Figure 2. Tensile stress-strain curves (left) and the amount of failed particles versus the far-field applied strain curves (right) for the different arrangements of particles (random, regular, clustered and gradient).

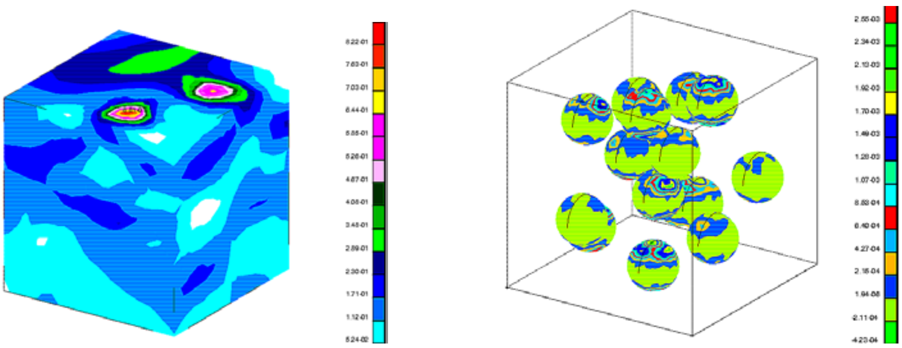

Figure 3. Distribution of equivalent plastic strains on box boundary (left), and on the particle/matrix interface in the microstructures with random particle arrangements (15 particles, VC =10%).

After the first particle fail, the flow stress of the composite increases with varying the particle arrangement in the following order: gradient < random < clustered < regular microstructure. One can see from Figure 3 that the rate of damage growth increases in the following order: gradient < random < regular < clustered.

The strength and damage resistance of a composite with a gradient microstructure strongly depends on the orientation of the gradient in relation to the direction of loading. In the case of the microstructure with vertical gradient (along the loading vector), the rate of particle failure is very low (about 6.35 particle/mm) and the particle failure begins at relatively high displacement loading, 0.2 mm. In the case of the microstructure with horizontal gradient (normal to the loading vector), the rate of particle failure is the same as for random microstructures.

CONCLUSIONS

Numerical analysis of the effect of microstructure, arrangement and volume content of hard damageable inclusions in plastic matrix on the deformation and damage growth has been carried out. The effect of the particle arrangement on the effective response of the material becomes significant only at the load at which the particles begin to fail. The flow stress of the composite increases with varying the particle arrangement in the following order: highly gradient < random < clustered < regular microstructure. The rate of damage growth increases in the following order: gradient < random < regular < clustered.

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